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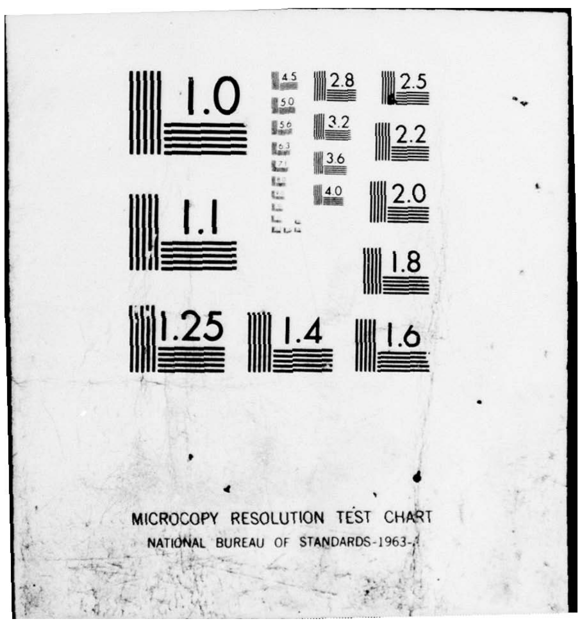
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LASER VELOCIMETER MEASUREMENTS IN TURBULENT AND MIXING FLOWS

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MARCH 1979

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in x, y and z, and the control of the polarization of light entering the beam divider. The flow system provides subsonic air flow over a rearward facing step simulating a dump combustor. The data collection and storage system consists of a high speed burst processor, a dedicated microcomputer for high speed data collection, and a floppy disc for data storage. Data processing is done on a CDC6500 computer connected to the system via a phone line. The system will be used to measure and document measuring biases in an LDV system in highly turbulent and mixing flows.

PREFACE

This interim report was submitted by the School of Mechanical Engineering of Purdue University, under Contract No. F33615-77-C-2010. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio under Project No. 2308 with Roger R. Craig/AFAPL/RJT as Project Engineer. Warren H. Stevenson and H. Doyle Thompson of Purdue University were technically responsible for the work.

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SECTION I

INTRODUCTION

The objective of this research program is to investigate the application of laser Doppler velocimetry to turbulent and mixing flows. Of particular interest are the various bias errors which are known to arise in such measurements. These errors may result from several effects including nonuniform particle seeding, flow reversal, particle path through the optical probe volume, optical alignment, and the nature of the signal processing used. All of these effects can be expected to affect measurements in recirculation zones such as those found in dump combustors. They will also affect measurement accuracy in any flow situation involving high turbulence and/or mixing. Since the errors can exceed ten percent in many turbulent flow cases, it is important to understand their origin and develop methods of correcting measured data or eliminating the biases completely by suitable measuring techniques.

A secondary objective of the research is to investigate the feasibility of using fluorescent particles in mixing studies. By using such particles it is possible to trace fluid elements originally present in only one input flow. This will be advantageous in determining bias errors in mixing processes and may also be helpful in analyzing the complex fluid mechanics involved.

Most of the effort during the first year of the program has been directed toward the design and development of a laser velocimeter system with the capabilities necessary to investigate the biasing problem in a rigorous manner. This system includes the basic optical package, a mechanical system for x-y-z traversing, the flow system, and a data processing system. All of these system components will be described in detail following a brief summary of the biasing problem.

SECTION II

THE BIASING PROBLEM

The basic equation for the common differential Doppler velocimeter is

$$f_D = \frac{2V\sin(\theta/2)}{\lambda} \tag{1}$$

where f_D is the measured Doppler frequency, V is the velocity component perpendicular to the fringe planes in the probe volume, θ is the beam intersection angle, and λ is the wavelength. λ is known and θ can be measured to high accuracy, so in principle the only limitation on measurement of the velocity component V is the accuracy with which f_D can be measured. However, in practice several difficulties arise, particularly when the mean velocity or turbulence intensity are to be determined from a set of measurements. A large number of effects have been identified which can "bias" the data to give an erroneous mean velocity. The term bias has been extended to include additional effects which tend to broaden the measured velocity histogram even if the mean velocity is not affected.

Thompson and Flack [1] have identified a total of ten biases which affect LDV measurements made with counter type (individual realization) signal processors. Additional biases have been discussed by other workers. Here we will only consider those biases which appear to be significant in recirculation zones and other flows of high turbulence intensity and those which may occur in mixing regions.

1. Particle Seeding Effects

The most obvious bias error is that arising from velocity slip between the fluid and the light scattering particles. A direct means of eliminating this effect is to only use particles small enough to accurately follow the flow. When this cannot be done for some reason a discriminator which rejects signals above a certain amplitude has been successfully used to reject data from the larger particles [2]. This minimizes the error but does not eliminate it entirely, since large particles passing through the edges of the probe volume will also produce small amplitude signals.

Another particle seeding effect is the uneven seeding bias resulting from an unequal distribution of particles in a homogeneous flow or in mixed flows.

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[1] Thompson, H.D. and Flack, R.D., Jr., "An Application of Laser Velocimetry to the Interpretation of Turbulent Structure," p. 189, Proceedings of the ISL/AGARD Workshop on Laser Anemometry, German-French Research Institute (H.J. Pfeifer and J. Haertig, eds.), St.-Louis, France (1976).

[2] Pfeifer, H.J., "Review of High Speed Applications of Laser Anemometry in France and Germany," p. 1, Proceedings of the NATO/AGARD Symposium on Applications of Non-Intrusive Instrumentation in Fluid Flow Research (AGARD-CP-193), St.-Louis, France (1976).

Asalor and Whitelaw [3] have shown this bias to be negligible in most homogeneous flows, but significant changes in measured mean velocity depending on the seeding approach have been noted in a mixing investigation [4].

2. Flow Effects

A bias which is flow dependent and also indirectly related to particle seeding is the individual realization or velocity bias first identified by McLaughlin and Tiederman in 1973 [5]. The idea is relatively simple. Proportionately more fast particles than slow ones pass through the probe volume. (The extreme case would be zero velocity which would never produce a signal.) Therefore if a simple (particle) average of the data is performed an erroneously high mean velocity should be obtained. Several correction schemes have been proposed including a 1/V weighting of the data as suggested by McLaughlin and Tiederman, random sampling [6], residence time weighting [7], or more involved methods [8]. Unfortunately there is still considerable disagreement as to the proper correction approach. Some workers have hypothesized that the slow moving particles may scatter more light than fast moving ones and thus be more readily detected. This would have the effect of automatically compensating for the velocity bias. However, a recent study seems to refute this [9]. Obviously the

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[3] Asalor, J.O. and Whitelaw, J.H., "The Influence of Combustion-Induced Particle Concentration Variations in Laser-Doppler Anemometry," p. 115, Proceedings of the LDA-Symposium, Technical University of Denmark, Copenhagen (1975).

[4] Barnett, D.O. and Giel, T.V., "Laser Velocimeter Measurements in Moderately Heated Jet Flows," AEDC-TR-76-156 (AD A038283) p. 35, (1977).

[5] McLaughlin, D.K. and Tiederman, W.G., "Biasing Correction for Individual Realization Laser Anemometer Measurements in Turbulent Flows," Physics of Fluids, 16, 2082 (1973).

[6] Durao, D. and Whitelaw, J.H., "The Influence of Sampling Procedures on Velocity Bias in Turbulent Flows," p. 138, Proceedings of the LDA-Symposium, Technical University of Denmark, Copenhagen (1975).

[7] George, W.K., Jr., "Limitations to Measuring Accuracy Inherent in the Laser Doppler Signal," p. 20, Proceedings of the LDA-Symposium, Copenhagen, (1975).

[8] Buchhave, P. and George, W.K., Jr., "Bias Corrections in Turbulence Measurements by the Laser Doppler Anemometer," p. 110, Laser Velocimetry and Particle Sizing (Proceedings of the Third International Workshop on Laser Velocimetry) H.D. Thompson and W.H. Stevenson (eds.), Hemisphere Publishing Corporation, Washington, D.C. (1979).

[9] Bogard, D. and Tiederman, W.G., "Experimental Evaluation of Sampling Bias in Naturally Seeded Flows," p. 100-109, Laser Velocimetry and Particle Sizing, Hemisphere Publishing Corporation, Washington, D.C. (1979).

problem of velocity bias is still an open question and carefully controlled experimental measurements are required to resolve the issue.

A second flow related bias is due to directional ambiguity which results from the directional insensitivity of a simple LDV. This can introduce large errors in measurements made in recirculation zones and other highly turbulent regions. The usual method of eliminating this problem is frequency shifting one of the input beams.

Frequency shifting can also be used in principle to minimize incomplete signal bias which results when particles with small velocity components perpendicular to the fringes pass through the probe volume. Beyond a certain angle insufficient fringes will be crossed to satisfy the processor and these signals will be lost, resulting in a measured mean velocity which is too high. This can be an important effect in highly turbulent flows. Whiffen et.al., have analyzed this problem in detail [10]. Obviously the size of the probe volume is an important factor.

3. Optical System Effects

The size of the probe volume must be considered in analyzing possible bias effects as was just noted. Another example of this occurs when measurements are made in steep velocity gradients such as near a wall. One assumes that all velocities are measured at the center of the probe volume, but of course the signals actually come from any point in the finite probe volume. Karpuk and Tiederman showed that in the near wall region of a turbulent flow the measured mean velocity could be 10% high and the turbulence intensity 100% too high [11]. However, in most flow regions the error is negligible.

Another optical effect is the frequency broadening which occurs if the intersecting beams do not meet at their waists. The error is usually significant only for low turbulence levels, however. Durst and Stevenson have carried out a detailed study of this problem [12].

---

[10] Whiffen, M.C., Lau, J.C. and Smith, D.M., "Design of LV Experiments for Turbulence Measurements," p. 197, Laser Velocimetry and Particle Sizing, Hemisphere Publishing Corporation, Washington, D.C. (1979).

[11] Karpuk, M. and Tiederman, W.G., "Effect of Finite Size Probe Volume Upon Laser Doppler Anemometer Measurements," AIAA Journal, 14, 1099 (1976).

[12] Durst, F. and Stevenson, W.H., "Influence of Gaussian Beam Properties on Doppler Signals," Applied Optics, 1979 (to be published).

SECTION III

VELOCIMETER OPTICAL SYSTEM

It is apparent from the discussion in the preceding section that the optical system configuration has a pronounced effect on the magnitude of several of the bias errors. Therefore the ability to vary important optical parameters was a major criterion in the design of the LDV system. Major features of the system which has been built include variable fringe spacing, variable beam diameter in the probe volume, precise control of the beam intersection point relative to the beam waist, provision for frequency shifting one or both input beams, the ability to easily rotate the instrument about the optical axis, the ability to traverse the probe volume in x, y and z and control of the polarization of light entering the beam divider in order to optimize signal modulation.

A schematic of the LDV optical system is shown in Fig. 1. A 5 watt argon laser (Coherent Radiation-Model 52) operating at the 0.5145 μm wavelength is utilized. This is followed by a collimating lens set which provides beam control as will be discussed later. The polarization rotator (Spectra-Physics, Model 310-21) allows rotation of the plane of polarization to maintain it perpendicular to the plane of the beam dividing prism for optimum intensity match and fringe contrast at the probe volume. This rotator utilizes a double Rhomb prism assembly and can be utilized over a 0.4-0.7 μm wavelength range with negligible insertion loss or polarization state error.

Two broadband all-dielectric morrors (Newport Research Corp.) are used to direct the beam leaving the polarization rotator on the lower level to the beam dividing prism on the upper level (Thermo Systems, Model 915-1). When frequency shifting is used one beam leaving the divider passes through an acusto-optic modulator (AOM), while the other passes through either a path compensating block or another AOM. The two beams then enter the beam separation control optics which consist of two precisely adjustable mirrors and a special prism having a reflective coating on two faces. A more complete description of the frequency shift and beam separation control systems is given in a subsequent subsection.

The remainder of the optical system is conventional, consisting of a focusing lens and a receiving optics package. More details are given below. It should be noted that the input optics on the upper level (beam divider through focusing lens) are on a platform which can be rotated about the optical axis so that different velocity components can be measured. The system as presently arranged is a one-component forward scatter LDV. However the design permits later modification for backscatter and/or two-component operation.

1. Beam Collimation System

The output beam from a laser operating in the TEM_{00} mode has a Gaussian intensity distribution and a divergence inversely related to its diameter. When such a beam is split by a beam divider into two parallel beams which are brought to intersection by a lens as in this LDV system, it is well known that the intersection does not generally coincide with the waists of the focused beams, This can introduce a broadening in the measured velocity spectrum [12]. In

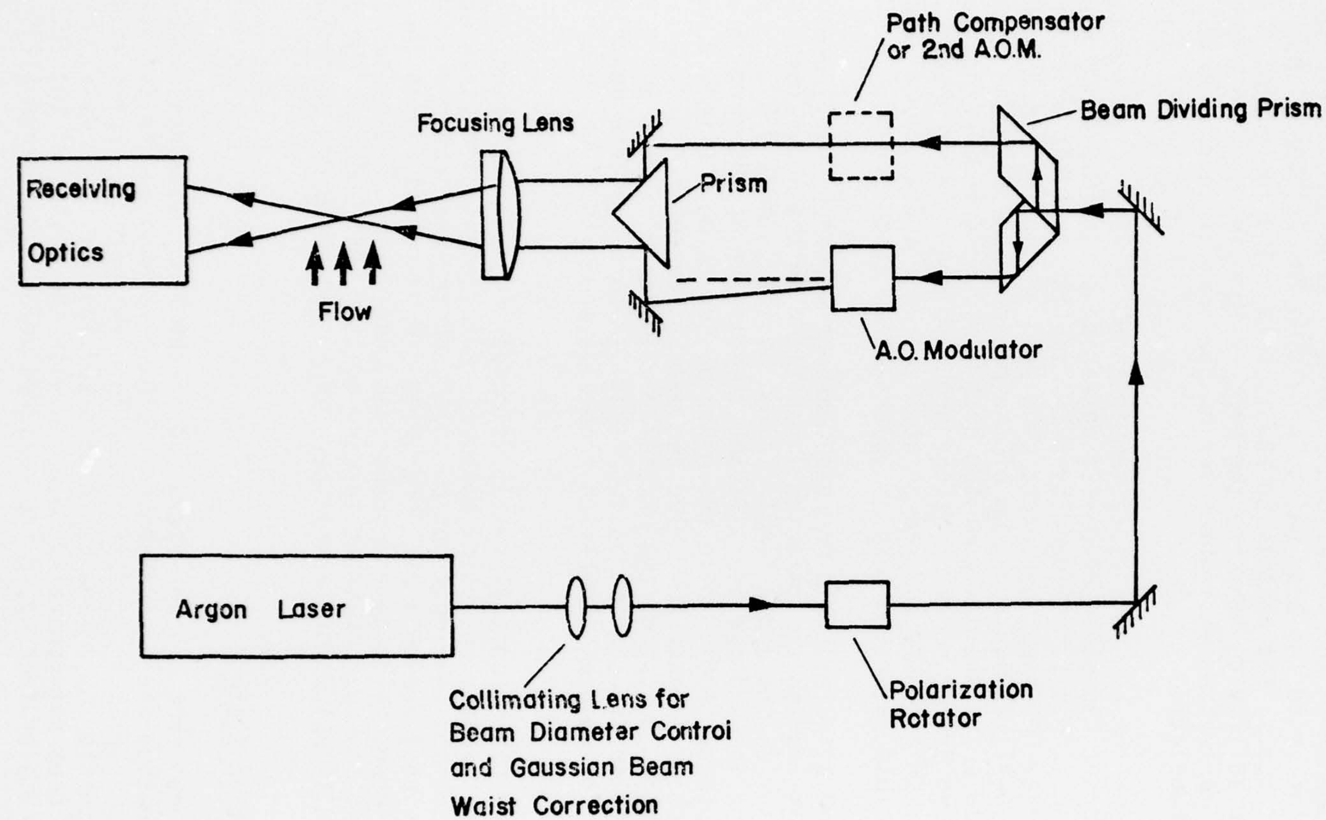

FIGURE 1: LDV Optical System

addition, signal quality is reduced, since the peak beam intensity may occur outside the probe volume. Therefore the collimating lens set is included in the optical system to provide the correct conditions for optimum beam intersection.

Adjustment of the waist position by means of the collimating lenses is actually required in the present case only when the system is used without the acousto-optic modulator and beam separation control optics. When these are in place, beam intersection following the focusing lens can be adjusted as desired by the mirrors which compensate for the angular offset introduced by the modulator. However, the collimating lenses are still useful, since they allow the beam diameter to be varied. This in turn permits the probe volume diameter to be changed, since it is inversely related to the input beam diameter at the focusing lens. A diameter increase of only about 50% can be achieved when the AO modulator is used due to its limited free aperture. This should be adequate to determine the effect of probe volume size on the data, however.

2. Frequency Shift and Beam Separation Control Elements

The optical system is designed so that either one or two acousto-optic (Bragg cell) modulators may be inserted to obtain a frequency difference between the input beams. The modulators (Intra Action Corp., Model ADM-40) have separate driving units which operate at fixed frequencies of 30 and 40 MHz. This allows frequency differences between the beams of 10, 30, 40 and 70 MHz to be obtained.

Optimum diffraction efficiency exists only when a Bragg cell is precisely oriented with respect to the input beam. Therefore each unit is mounted on a rotating base with an angular position resolution of 10 seconds of arc. This adjustment determines both the diffraction efficiency and whether the beam is shifted up or down in frequency. Details of the rotating base are shown in Fig. 2.

Since the frequency shifted beam leaving a Bragg cell is angularly deflected by a small angle (on the order of 5 milliradians), some means of providing alignment of the two input beams for proper intersection after the focusing lens is required. This is achieved with the beam separation control unit consisting of two mirrors and a 90^{o} prism. The unit is shown in Fig. 3. When only one modulator is used one mirror can be fixed. The other is placed on a high resolution mount (Newport Research Corp., Model 600-2) which is settable to 0.5 arcseconds in two orthogonal directions. This precision is required to obtain optimum beam intersection at the probe volume. When two Bragg cells are used both of the mirrors must be mounted on such mounts.

Beam separation, and therefore beam intersection angle, is controlled by the moveable prism. Distance between the beams can be varied between 4 and 40 mm. This allows the fringe spacing to be varied over a ten to one range (without changing probe volume diameter) with a given focusing lens.

As noted previously the angular control provided by the adjustable mirror also allows the beam intersection point to be made coincident with the waists of the focused beams. At present this alignment is accomplished visually. A more precise method is under development.

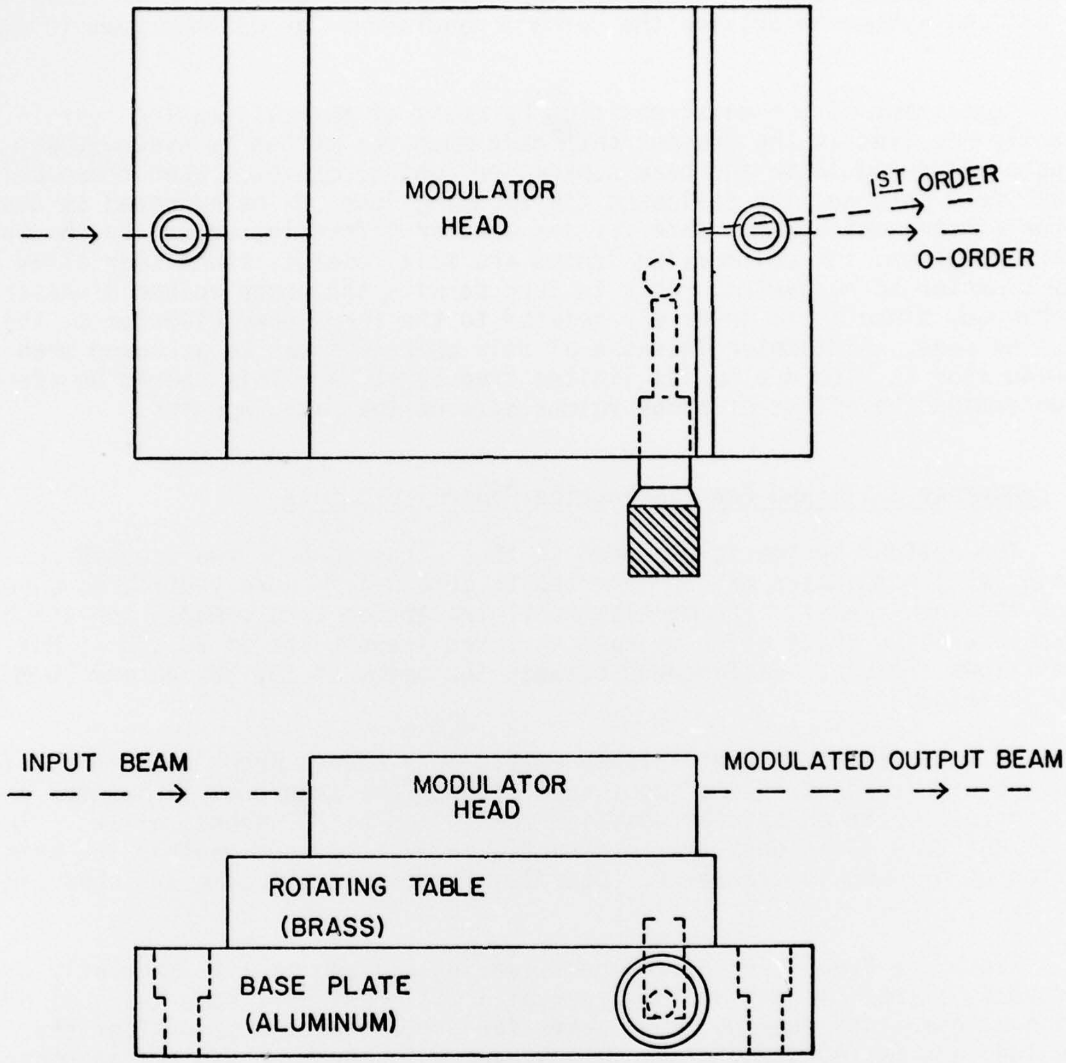

FIGURE 2: Acousto-Optic Modulator, Assembly View

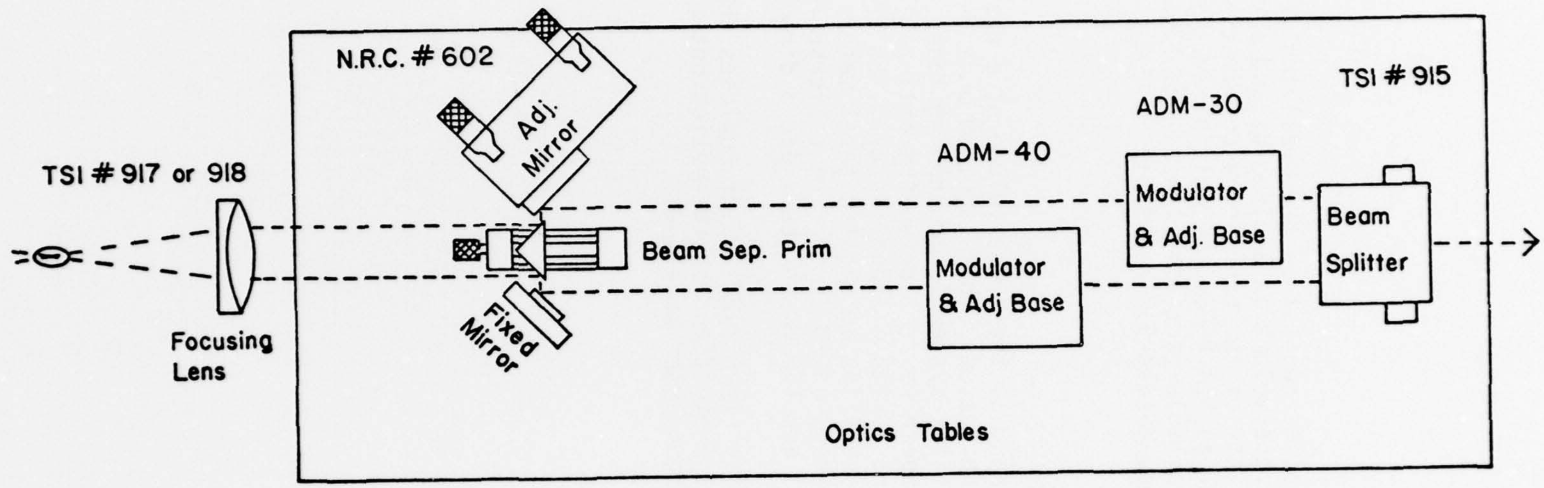

FIGURE 3: Transmitting Optics Component Diagram

3. Receiving Optics

The receiving optics consist of the receiving lens set, an adjustable mirror to image the probe volume on a pinhole, and a detector package. The detector package consists of the pinhole, a collimating lens, a narrowband filter (0.5145 μm) and an RCA 8575 photomultiplier. These elements are illustrated in Fig. 4. Available receiving lenses are 120.6 and 250 mm in focal length (Thermo Systems, Models 917 and 918).

4. Traversing System

Precise positioning of the probe volume at a desired flow point is provided by the traversing system. This is based on a 3-axis mill table which carries the entire optical system including the laser. Three Bodine DC gearmotors with variable speed control drive the mill table. Linear potentiometers (New England Instruments) with a linearity of 0.25% are used to obtain an electrical readout of position on digital panel meters which read directly in millimeters to an accuracy of ±0.1 mm. The traverse range is 254 mm in the y (vertical) direction and 152 mm in the x and z directions.

An amber Plexiglas (Type 2422) cover encloses the optical system and provides not only dust protection for the optics but also is a safety covering since it blocks the argon laser wavelength.

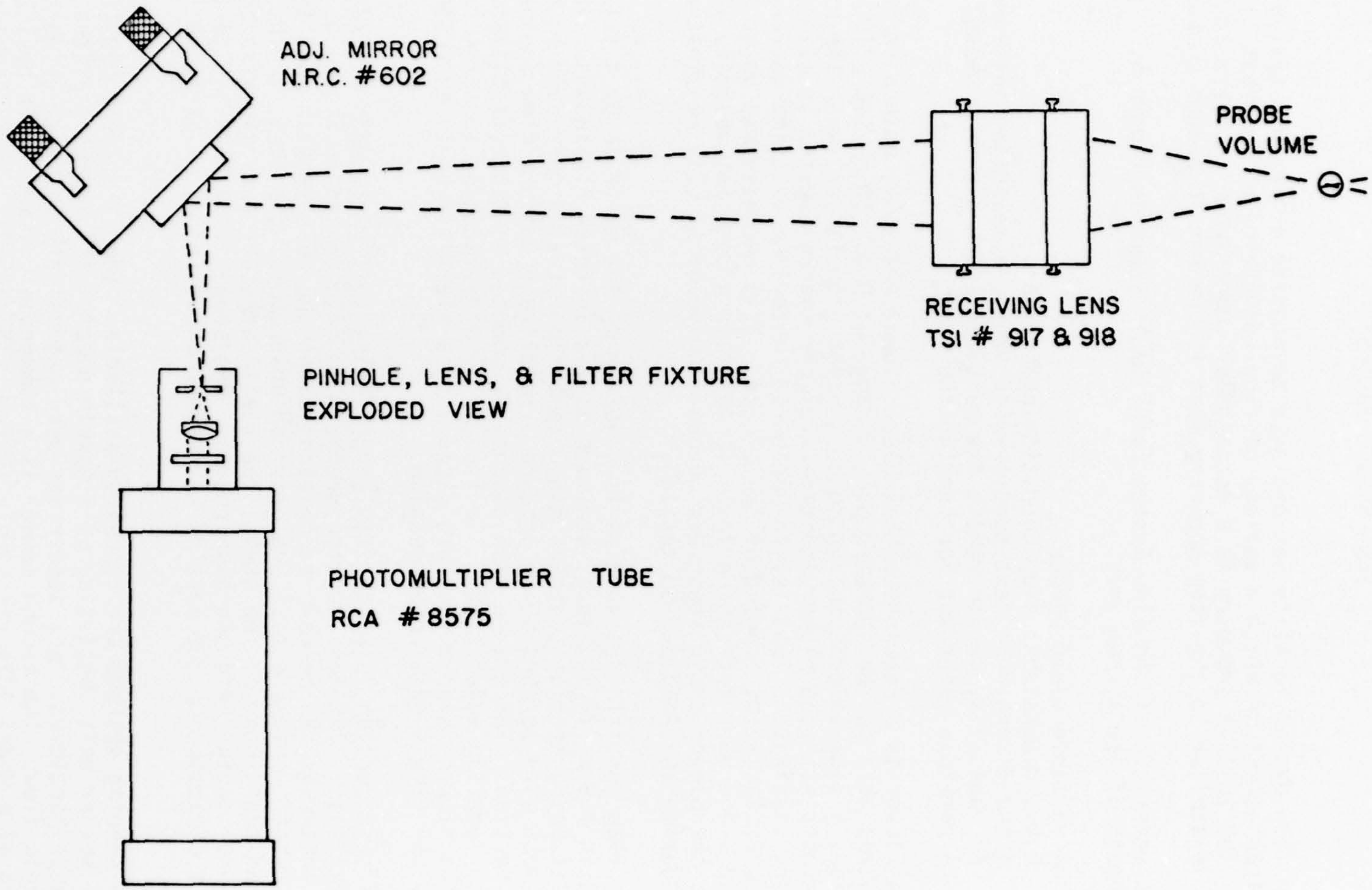

FIGURE 4: Receiving Optics Component Diagram

SECTION IV

FLOW SYSTEM FACILITY

The flow system facility was designed to provide a flexible system with easy optical access in which a variety of flow geometries of interest can be modeled. The initial geometry is a rectangular channel over a rearward facing step and is similar to the flow geometry that is present in a dump combustor.

The schematic of the Flow System Facility is shown in Figure 5. The main elements of the system are:

1. A variable speed blower.
2. A two-dimensional flow conditioning section.
3. A two-dimensional test section with pressure measuring instrumentation.
4. An exhaust system to remove the particle laden air (not shown).
5. A particle generator for seeding the flow.

The blower is a Peerless radial blade blower (PWB14GA) with a variable speed control that can be operated over a range of 0 to .50 m^3/sec (1100 CFM) and provides a flow velocity of up to 50.3 m/sec (165 ft/sec) with the present system. Tests with the blower indicate that the control system is slightly temperature sensitive. That is, the measured centerline velocity decreases slightly over long time running of the blower. This decrease may be as much as 3% over a one hour testing period. To maintain a constant velocity for the tests the blower shaft speed and tunnel flow velocity will be monitored and adjusted during any long period testing.

The flow conditioning section is a 102 mm by 102 mm (4 in by 4 in) square duct that is 1.9 m (74 in) long, and made of 1/2 in thick Plexiglass. The flow conditioning section contains honey comb flow straighteners and both coarse and fine mesh wire screens which produce a relatively uniform flow approaching the test section. The entire flow channel is mounted on concrete pillars with height and leveling adjustments. To isolate blower vibration from the test section the blower is on a separate stand with a flexible joint connecting the blower to the flow conditioning section.

The test section like the flow conditioning section is made of 1/2 in thick clear Plexiglass. The test section geometry is illustrated in Figure 5. Pitot pressure traverses can be made at stations along the test section and, in addition, static pressure taps are provided upstream of the step, in the base region, and downstream of the step. The static pressure taps can also be used to introduce seeding into the base region. The seeded flow from the test section is exhausted to the outside to prevent accumulation of particle laden air.

Two seeding systems are currently available. The first is a DOP (Dioctylphtalate) seeder unit consisting of a Laskin nozzle with impactor plates to remove large particles. This seeder was used extensively in previous work in a supersonic flow. The second seeder is a commercial system built by TSI and consisting of a Model 3074 air supply system, a Model 3076 Liquid Atomizer, and a Model 3072 Evaporation-Condensation Monodisperse Aerosol Generator. DOP is also used in the TSI unit, which provides controlled particle size and number density seeding.

It is anticipated that a benzyl alcohol-ethylene glycol mixture will be used for the tests with fluorescent dye tracers.

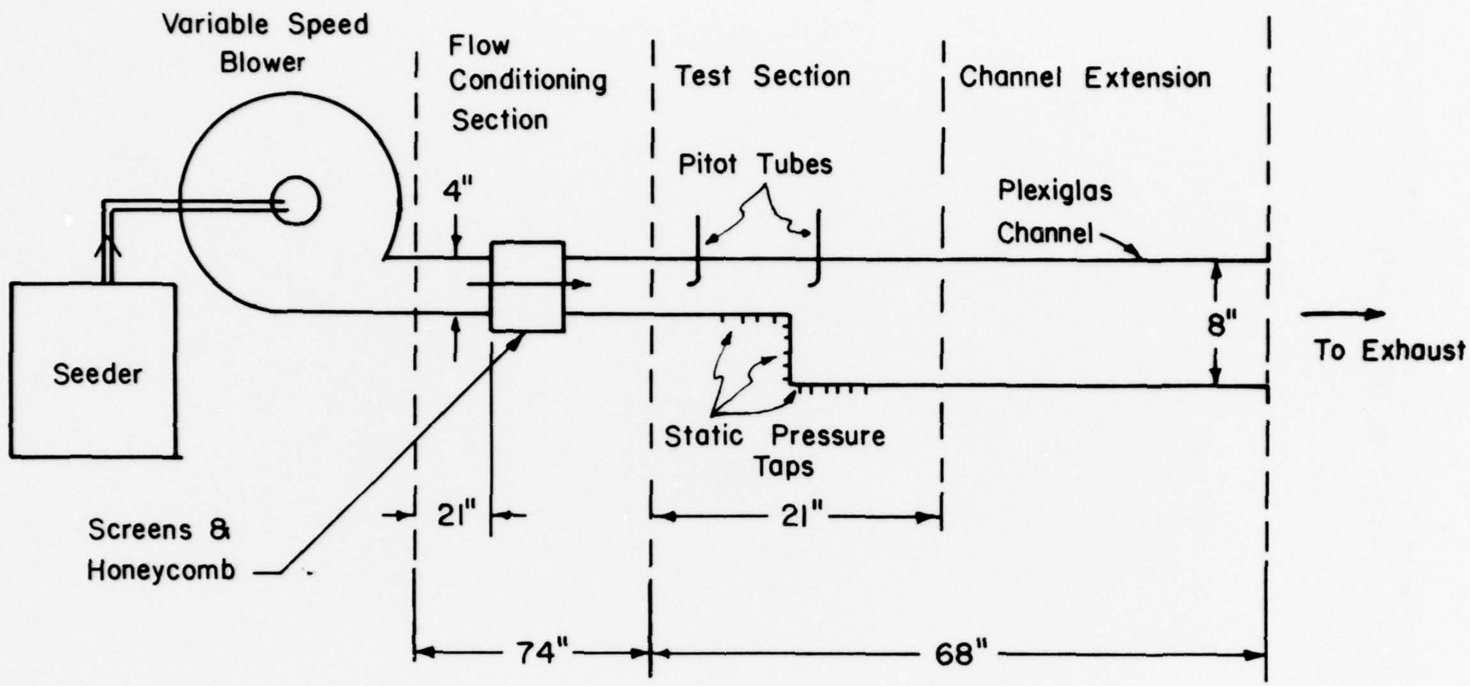

FIGURE 5: Flow System Facility

SECTION V

DATA COLLECTION, STORAGE AND PROCESSING SYSTEM

The data collection, storage and processing system is shown schematically in Figure 6. The output signal from the photo multiplier tube is fed to a signal processor unit. Two different processor units are available. The first is a high speed unit built at Purdue under a previous contract with the U.S. Army Missile Command and is described in detail in Ref. [13]. The second is the commercially available TSI model 1980. Operation of the TSI processor is described in the Instruction Manual, Ref. [14].

Although the original intention was to use the Purdue processor exclusively, partial failure of the unit and the realization that data from a "one of a kind" processor would be less useful to other researchers has led to obtaining a TSI model 1980 processor which will be used for the majority of the research. The Purdue unit will be used as a back-up unit and may be used for limited comparison studies.

The processor data rate depends on the seeding density and the amplifier setting (which effectively sets the trigger level). Data rates may be as low as a few per second to rates in excess of 20,000 per second. To collect and store this data a dedicated microcomputer (IMSAI 8080) with periphral equipment is used. The IMSAI 8080 was chosen for its flexibility, low cost, and compatibility with several other systems being used at Purdue. The design, construction, and software programming of the microcomputer facility has been one of the major portions of the effort to date.

Figure 6 illustrates the major units of the data collection, storage and processing system. The signal from the TSI processor will normally be transmitted as a digital signal directly to the microcomputer. The option to transmit an analog voltage is also available. However this option requires digital to analog conversion in the processor and subsequent analog to digital conversion in the microcomputer and will not be the normal mode of operation.

Supporting data such as pressures and position information can also be read as part of the data package. The processor data is then stored either on a floppy disc and/or is transmitted over phone lines to Purdue's main computer, the CDC 6500.

Although some data conditioning is done by the microcomputer, the data analysis is all done through FORTRAN programming of the CDC 6500. A FORTRAN program has been developed which reads the data stored on disk, and performs some statistical manipulation. The program consists of a main routine and four subroutines.

---

[13] Zammit, R.E., Stevenson, W.H., and Pedigo, M.K., "A Processor for High Frequency Burst Signals," IEEE Transactions on Instrumentation and Measurements, IM-25, 235 (1976).

[14] Instruction Manual for TSI Model 1990 Counter, Thermo-Systems Incorporated, St. Paul, Minnesota.

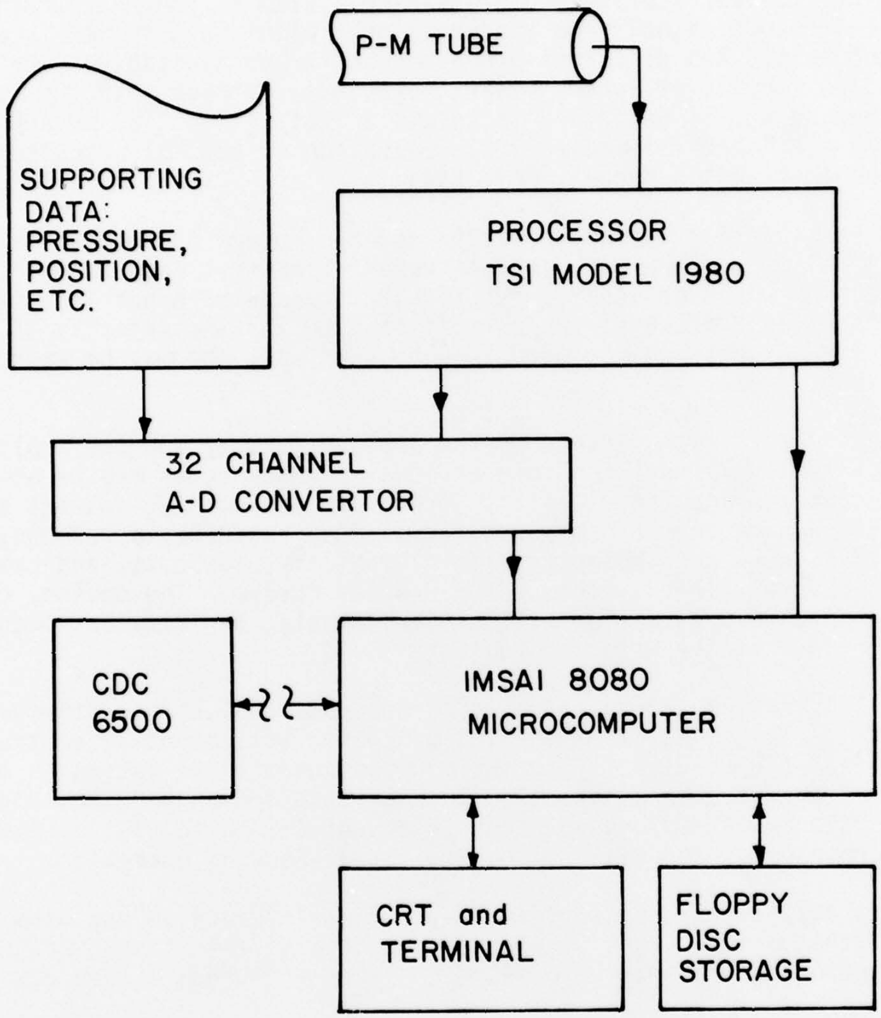

FIGURE 6: Data Collection, Storage and Processing System

The main routine reads the data from the disk and converts the digital information to a Doppler frequency by the following formula:

$$f_D = \frac{N \times 10^9}{D_m \times 2^{n-2}} \tag{2}$$

where N is the number of cycles per burst, n is the exponent, and D_m is the digital mantisa. The Doppler frequency is used to calculate the fluid velocity through the formula:

$$V = \frac{(f_D - f_s)\lambda}{2 \sin(\theta/2)} \tag{3}$$

where f_D is the Doppler frequency, f_s is the frequency shift, λ is the laser wavelength, and θ is the angle between the beams. Once all of the velocities are found, the main routine calls subroutine STATS to do the statistical manipulation.

STATS finds the particle average velocity, $\overline{V}$, the variance (turbulence intensity), σ^2, the standard deviation of the data set, σ, and the standard deviation from the mean, σ_m, as given in the following standard equations:

$$\overline{V} = \frac{1}{n} \sum_{i=1}^{n} V \tag{4}$$

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (V - \overline{V})^2 \tag{5}$$

$$\sigma = \sqrt{\sigma^2} \tag{6}$$

$$\sigma_m = \frac{\sigma}{\sqrt{n}} \tag{7}$$

A histogram of the data is plotted using subroutines HIST and USHV1. The program also contains a subroutine called SELECT. SELECT edits the original data set by removing any data points that do not lie within a specified number of standard deviations from the mean. As before, STATS, HIST and OSHV1 are called to determine the statistical quantities and plot a histogram of the revised set. Additional subroutines will be developed as needed.

Presently, modifications are being made to incorporate time information from a high speed clock which will be added to the microcomputer. Time information will be recorded with each sample. This will allow the recording of elapsed time between individual signals so that processing techiques based on both time and particle averages can be compared.

SECTION VI

CONCLUSIONS

A laser velocimeter flow measurement facility including a flow system and advanced data processing system has been designed and fabricated. The facility will allow carefully controlled measurements to be made in highly turbulent and mixing flows simulating those found in dump combustors. This will allow the biasing problems expected in such flows to be investigated in detail.

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